Development, design and performance analysis of a forced draft clean combustion cookstove powered by a thermo electric generator with multi-utility options

Perumal Raman*, Narasimhan K. Ram, Ruchi Gupta

The Energy and Resources Institute (TERI), Darbari Seth Block, India Habitat Centre, Lodhi Road, New Delhi 110003, India

1. Introduction

Across the world, about 2679 million people, rely on traditional biomass as a fuel for meeting their cooking energy requirement [1,2]. Almost 80–90% of the energy used in rural household is for cooking and water heating [3], of which 75–95% of the energy is from wood and charcoal [3]. Most of the biomass-fired cookstoves perform at a poor efficiency and emit harmful pollutants like CO and particulate matter. The indoor air pollution from the use of traditional cookstoves causes risks to health and even leads to premature death. It is essential to have biomass cookstoves providing clean combustion and higher efficiency. Many of the improved cookstoves do not fulfill their claim of fuel saving [4]. Many improved wood stoves have been developed, but they do not offer good control of the cooking power [5].

The World Health Organization (WHO) reports, about two million people die prematurely from illness due to indoor air pollution from burning of household solid fuel [6]. While the amount of particulate matters emitted from a traditional cookstove can be as high as 1002.3 μg m⁻³ the emission of particulate matter from an improved cookstove can be as low as 266.2 μg m⁻³ [7]. The average value of CO emitted from a traditional cookstove is 14.3 ppm (with SD as 13.1 and GM as 9.5) as compared to the emission of CO from an improved cookstove is 1.8 ppm (with SD as 3.2 and GM as 0.5) [7]. Thus, in comparison to traditional cookstoves, improved cookstoves reduce the emission of particulate matter by 74% and that of CO by 87%. The gasifier stoves can reduce the emission of particulate matter substantially to the order of 90% [8]. It may be noted that the suggested benchmark for CO emission from improved cookstove should be less than 20 g for completing a 5 dm³ water boiling test (WTB) [9]. Forced draft cookstoves are more expensive than the improved cookstoves which work on natural draft. Use of forced draft cookstoves is site specific, since most of the remote locations lack access to electricity. About 2.7 billion people would still rely on biomass for cooking [10]. Requirements of external power source and battery backup are acting as barriers for promotion of forced draft cookstoves. Thermo electric generator (TEG) is an alternative solution to have a forced draft cookstove without depending on an external power source. The objective of the present research work was to develop a TEG powered cookstove which generates its own power and eliminates dependency on external power supply. The TEG powered cookstove
can be used to generate a small amount of power to illuminate LED lights and charge mobile phones.

1.1. Thermo electric generator

The thermo electric effect was first discovered in 1822 by Seebeck, who observed that an electrical current would flow in a circuit made from two dissimilar metals, with the junctions at different temperatures [11]. The TEG module comprises of semiconductor materials, which generates power using the temperature difference between the two surfaces. The maximum temperature of the hot surface of a TEG module can withstand up to 325 °C; however, the fireplace temperature of a forced draft cookstove is more than 1000 °C. The TEGs available in the market are made with Bismuth Telluride (Bi2Te3) which can work at the temperature, as high as 260 °C (continuously) and intermittently at 380 °C [12]. Performance of TEGs which can withstand 800 °C was reported by Park [13]. With the available models of TEG, maintaining the temperature of the hot face, below the threshold limit is a challenge.

1.2. Multi-utility options

Forced draft cookstoves are expensive in comparison with the improved natural draft cookstoves. When the cost of cookstoves is high, it goes beyond the purchasing capacity of the people. Fuel saving alone cannot payback the increased cost of the forced draft cookstoves. In most of the cases, fuels for the cookstoves are agro residues, dung cake and biomass collected from own trees and the roadside bushes [14]. The economic viability of the TEG cookstoves can be increased by providing options for multiple uses like LED lighting and charging of mobile phones. Unlike solar power generation systems, TEG can produce power both during the day as well as the night and even on cloudy days [15]. TEG is more reliable and has many advantages over conventional electric generators and it does not produce noise as there are no moving parts [16]. Experiments on a 6 W TEG module and a biomass cookstove were carried out [15]. A cooking pot coupled with TEG, called the “Wonder Pot” was used to charge a cell phone [17]. While cooking, “Wonder Pot” was able to produce 5 V DC with ~7 W power output. The cost of the whole device was US $ 102 in 2013. A camp stove, which also has the facility for mobile phone charging, was introduced to the market at a cost of US $ 129, in 2013 [18]. This cookstove is designed to provide a power output of 2 W for charging a mobile phone.

2. Objectives

The objective of the present study is to design and develop a TEG powered clean combustion forced draft cookstove that works with higher efficiency. It was aimed at optimizing the material and geometry of the cookstove to reduce the cost involved in fabrication. The present study is also focused on design and development of a TEG powered cookstove with multi-utility options like charging of mobile phones and operating LED lights, to increase the economic viability and adoptability of the cookstove.

3. Methodology

Development of the TEG powered cookstove involved three major activities, these are as follows:

i. Design and development of a TEG system to supply sustainable quantity of the required power output.

ii. Design and development of a TEG powered cookstove to maximize its efficiency and optimize the fabrication cost; and

iii. Enabling the TEG powered cookstove to provide multi-utility options like mobile phone charging and LED lighting.

3.1. Design parameters: cookstove

Cookstoves need to be designed and constructed according to the consumer preferences and should save fuel, time and effort [19].

Availability of electricity from an uninterrupted power supply is the basic requirement of forced draft cookstoves. In order to overcome this issue, TEG was selected to provide the power required to operate the DC blower used in the forced draft cookstoves. The parameters selected for the design and development of the TEG powered forced draft cookstove are presented in Table 1 along with their performance indicators and benefits. The design parameters listed in Table 1 were optimized to increase the overall performance efficiency of the TEG powered cookstove.

3.2. Design parameters: TEG

The design of the TEG should be such that it is able to provide the required quantity of power to operate the DC blower according to the wood burning rate of the cookstove. The TEG is the key component which influences the performance of the TEG powered forced draft cookstoves. A set of parameters for optimizing the performance of the TEG was selected. The details of the parameters selected to optimize the performance of the TEG are presented in Table 2, along with their performance indicators and benefits. It may be noted from Table 2, the TEG was designed to provide a power output of 5.0 W, which is sufficient to operate a small DC blower and also to charge mobile phones and operate LED lights.

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**Table 1**
The details of the parameters selected to design the TEG cookstove.

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Parameters</th>
<th>Performance indicator</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermal efficiency</td>
<td>More than 40%</td>
<td>Fuel saving</td>
</tr>
<tr>
<td>2</td>
<td>Firepower</td>
<td>Close to 4 kW (during hot-start high-power phase)</td>
<td>Time saving</td>
</tr>
<tr>
<td>3</td>
<td>Turndown ratio (firepower reduction during simmering phase)</td>
<td>A reduction 50% firepower comparing the firepower of hot-start high-power phase</td>
<td>Fuel saving</td>
</tr>
<tr>
<td>4</td>
<td>Low surface temperature</td>
<td>Below 50 °C</td>
<td>Safety aspect</td>
</tr>
<tr>
<td>5</td>
<td>Stable structure</td>
<td>User satisfaction</td>
<td>Safety aspects</td>
</tr>
<tr>
<td>6</td>
<td>Ease of initial firing and operation</td>
<td>Easy and quick, without much smoke</td>
<td>Increased comfort level</td>
</tr>
<tr>
<td>7</td>
<td>Cost optimization</td>
<td>Less than US $ 50</td>
<td>Increased affordability</td>
</tr>
<tr>
<td>8</td>
<td>Independent of local grid</td>
<td>Sufficient power generation to run the DC fan</td>
<td>Can work in places, where there is no power</td>
</tr>
<tr>
<td>9</td>
<td>Multi-utility option</td>
<td>Charging of cell phone and battery for LED lighting</td>
<td>Charging cell phone or stored power for LED light</td>
</tr>
</tbody>
</table>
3.2.1. Selection of TEG components

The TEG uses several components to convert a small amount of heat from the cookstove into electricity. The TEG system comprises of four components namely a TEG module, a heat receiver, a heat sink and a blower fan. The TEG module is the basic component which converts heat into electricity. One side of the TEG has to be kept at a high temperature (about 300 °C) while the other side has to be kept at a low temperature (below 60 °C). The power output of the TEG is directly proportional to the temperature difference between the hot side and cold side of the TEG. It needs to be noted that the hot side of the TEG cannot be raised beyond a certain temperature as specified by the manufacturer as its threshold temperature. A stainless steel (SS) rod was used to receive the heat from the combustion chamber and transfer the heat to an SS plate. The SS plate distributes the heat uniformly to the hot side of the TEG. The cold side of the TEG is connected to a heat sink. A DC blower is used to cool the heat sink to remove the heat effectively from the TEG. The details of the components selected for the TEG system is presented in Table 3. A schematic diagram of the TEG system along with the details of its components is shown in Fig. 1. From Fig. 1, it may be noted that, a heat receiver is used to absorb the heat from the combustion chamber and transfer it to the TEG module to maintain the hot side of the TEG at high temperature. Further, a heat sink is used to keep the cold side of the TEG module at a low temperature. The heat sink is provided with a large surface area to increase the heat transfer rate. The DC blower is located just before the heat sink to blow air directly on it and removes the heat received by the TEG. The power output of the TEG is directly proportional to the temperature difference between the hot side and cold side. TEGs have a threshold limit for the maximum temperatures. The components of the TEG have to be designed appropriately to maintain the temperature of the hot side and cold side within the temperature range specified by the manufacturer and ensures best performance and durability of the same.

### Table 3

<table>
<thead>
<tr>
<th>Components</th>
<th>Specification</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG</td>
<td>5 V, ~ 5 W</td>
<td>Sufficient to ruin a 1.5 W DC fan also for charging a mobile phone and LED light</td>
</tr>
<tr>
<td>Heat receiver</td>
<td>To withstand at 1200 °C</td>
<td>Heat flow at a rate in which the hot side is maintained at 300–325 °C</td>
</tr>
<tr>
<td>Heat distributor</td>
<td>5 mm thick SS plate with smooth surface</td>
<td>Uniform heat distribution to improve the efficiency and durability</td>
</tr>
<tr>
<td>Heat sink</td>
<td>Large surface area with higher heat transfer rate</td>
<td>Surface area adequate to maintain the surface temperature close to 60 °C</td>
</tr>
<tr>
<td>Cooling fan</td>
<td>DC fan: 5 V, 1.5 W</td>
<td>Airflow adequate to keep the heat sink close to 60 °C</td>
</tr>
</tbody>
</table>
temperature in the combustion chamber. The TEG powered cookstove is provided with two layers of air gap with a layer of insulation made up of ceramic wool. The gaps and the insulation layer help reduce the overall heat loss from the external surface of the cookstove and to increase the thermal efficiency of the cookstove. A schematic diagram of the TEG powered cookstove along with its components is shown in Fig. 2.

3.4. Experimental analysis of the performance of the TEG powered cookstove

The performance of the TEG powered forced draft cookstove was evaluated by using a WBT version 4.2.2 [20]. The WBT consists of three phases namely:

- Phase I: cold-start high-power phase.
- Phase II: hot-start high-power phase.
- Phase III: simmering phase.

The WBT involves boiling of 5 dm³ of water through two phases namely, Phase I and Phase II. Subsequently, during Phase III, the water temperature is maintained in the range of 96–97 °C. The wood was kept in packets of 125 g each to estimate the fuel intake during individual phases of the WBT. In this process in addition to the estimation of the quantity of the wood consumed, the variation in the wood consumption rate within a particular phase can also be obtained. The total quantity of wood consumed during each phase of the WBT was estimated by Eq. (2)

\[ \text{FW}_{\text{ph}} = (125 \times N_p) - R_l \] (2)

During the high-power phases, the efficiency of the TEG powered cookstove was estimated by Eq. (3)

\[ \eta_{hp} = \left( \frac{W_{W} + (W_{e} \times C_{p})}{(T_2 - T_1) + W_{e} \times L_{ew}} \right) \times \left( \frac{\text{FW}_{\text{ph}}}{\text{CV}_{fw}} \right) \] (3)

During the simmering phase, the efficiency of the TEG powered cookstove was estimated by Eq. (4)

\[ \eta_{sp} = \left( \frac{W_{e} \times L_{ew}}{\text{FW}_{\text{sp}} \times \text{CV}_{fw}} \right) \] (4)

Firepower was estimated during each phase of the WBT. Firepower is the rate of energy input to the cookstove, which determines the duration of cooking. When using a cookstove it is essential to ensure that the cookstove provides sufficient firepower to cook the food within the same time or even quicker than the traditional cookstoves. The firepower of the TEG cookstove was estimated by using Eq. (5).

\[ F_{h} = \left( \frac{\text{FW}_{\text{ph}} \times \text{CV}_{fw} \times 60}{d_{\text{ph}}} \right) \] (5)

Turndown ratio of the cookstove was estimated to evaluate the control over the firepower. Turndown ratio (TDR) is the ratio of firepower during the hot-start high-power phase to the fireplace during the simmering phase. The firepower is at its maximum during the hot-start high-power phase and minimum during the simmering phase. Turndown ratio of the TEG stove was estimated by Eq. (6)

\[ \text{TDR} = \frac{F_{hh}}{F_{sp}} \] (6)

Specific fuel consumption rate (SFC) is the quantity of wood consumed to boil and simmer 1.0 dm³ of water during the WBT. SFC of the TEG powered cookstove was estimated by Eq. (7)

\[ \text{SFC} = \left( \frac{\text{FW}_{\text{th}} + \text{FW}_{\text{sp}} \times \text{CV}_{fw}}{(T_2 - T_1)} \right) \times \frac{1}{Q_{fw}} \] (7)

3.5. Multi-utility options

The TEG powered cookstove is designed to produce 5.0 W power at 5.0 V DC. Out of the 5.0 W power, 1.0 W is sufficient to operate the DC blower to create the forced draft. The remaining power can be stored in Li-ion batteries and can thereon be used for applications like mobile phone charging and LED lighting. An Li-ion battery charger designed for mobile phone charging would cost about US $20 (in 2013). In India, about 1.15 lakh villages do not have access to electricity [21]. People living in such remote villages can be benefitted with the use of TEG powered cookstoves and the small power generated from such cookstoves. In this manner, the TEG powered cookstove was designed for multi-utility options. To enhance the multi-utility options, various methods used for charging the battery (using the power generated by the TEG) were studied and analyzed.

3.6. Experimental setup

The experimental setup of the present study consists of two streams of analysis. One is to study and analyze the performance of the TEG system. The other is to study and analyze the performance of the cookstove. The performance of the cookstove and the TEG system were optimized based on the observations made during the experiments. The TEG powered forced draft cookstove was optimized to maximize its thermal efficiency and power output of the TEG system. The standard WBT was conducted to estimate the thermal efficiency of the cookstove. During the experiment, the speed of the DC blower and the power output of the TEG system were monitored and analyzed. An Li-ion battery charger with a built-in DC–DC converter was used to test a cookstove with lighting and mobile charging capabilities. Wood from the same lot was used for conducting the experiments to avoid any variation in the result due to variation in the fuel property. Wood pieces of 100 mm long with a cross-sectional area up to a maximum of 20 mm × 20 mm was used during the evaluation of the cookstove and the TEG system. The wood pieces were weighed and kept in
eight packets of 125 g each. The variation in firepower can be closely monitored by using a measured quantity of wood during the experiment.

3.7. Equipments used

Different types of equipments were used to study the performance of the forced draft cookstove and the TEG system. A digital multi-meter was used to measure the voltage and the power output of the TEG. A tachometer was used to measure the speed of the fan in terms of revolutions per minute (RPM). A hot wire anemometer was used to measure the velocity of the airflow generated by the DC fan. A digital thermometer was used to measure the temperature and the temperature of TEG components. A digital balance was used to measure the quantity of water and wood consumed during the experiment. The details of the equipment used while conducting the experiment and their specifications are presented in Table 4. From Table 4, it may be noted that the accuracy of the equipment used in the experiments ranges from ±0.03% to ±1.2%.

4. Results and discussion

4.1. Optimizing the design configurations of the TEG powered forced draft cookstove

The design configuration of the TEG powered forced draft cookstove was optimized, without affecting its performance. A set of nine parameters (Table 1) was considered for designing the TEG powered forced draft cookstove. Apart from the performance efficiency, cost of the cookstove has a strong influence on the large-scale dissemination of the same. The focus was to optimize the cost of the TEG components as well as the overall cost of the TEG powered forced draft cookstove.

4.1.1. Optimizing the cost of the TEG

In a TEG powered forced draft cookstove the cost of the TEG accounts for 46% of the total cost of the cookstove. A detailed cost analysis was carried out in terms of power output and cost of the cookstove. As TEG is one of the new upcoming areas for generation of small power, only a few manufacturers are available for manufacturing TEG modules. A TEG module to produce 5.0 W of power output at 5.0 V DC was selected to use in the TEG powered forced draft cookstove. Two models of TEG viz. Model I [22] and Model II [23] are available in the preferred range, but there is a huge difference in the cost of the TEG models. Another TEG module Model III [24] is also available, the cost of which is reasonable in terms of power generation capacity (US $ W⁻¹). However, the design capacity in terms of power output is much higher in the order of 14 W, which is almost three times the value of the preferred power output. The module referred in Ref. [24] can be a potential choice where the focus is to have an efficient and clean combustion TEG powered forced draft cookstove, with higher power output. The TEG using Model III can be used to serve a specific group of users with an objective to meet both their cooking and lighting requirements with equal thrust. In the present study, as the main objective is to design and develop an affordable TEG powered forced draft cookstove with a small power generation capacity, the TEG referred as Model I was selected. The comparison of the design specifications of three models of TEG modules and their respective cost is presented in Table 5.

Development activities of TEG are carried out by several research institutes to improve the efficiency and to reduce the cost. A full intermetallic compound (IMC) through solid–liquid inter-diffusion (SLID) bonding were explored in TEG assembly process, to withstand high temperature [25]. TEG powered cookstoves are considered as a low cost solution for obtaining light from the stove [26]. Locally available minerals were identified and tested for the construction of TEG [27]. With locally available minerals, 66 mV was generated at a temperature difference of 88 °C. The efficiency of the TEG was improved by 72.7% by using phase change materials instead of air-cooling [28]. Improvement in heat transfer component and optimizing the materials can result in reduction of the TEG cost. Research on construction materials can bring down the cost of TEG. Performance of TEG was analyzed with variation in height [29]. It was reported that the height of the TEG must be above 3 mm to maximize the power generation; in the present study the TEG used was 4.8 mm.

4.1.2. Optimizing the cost of the TEG powered cookstove

The cost of a cookstove is one of the factors which influence the adoptability of cookstoves by its users. For a successful entrepreneurship development and commercialization, pricing and financial scheme for cookstoves are considered as key requirements [30]. Price of a cookstove can be a significant barrier for adoption and a payback period of 1–3 months is preferred by the consumers [19]. In the present study, the cost of the cookstove was optimized by the selection of appropriate components for the cookstove and the TEG. The cost of the cookstove was optimized by considering its geometry and costs associated with the metal sheet, insulation materials and labor. The cost of the cookstove was optimized by developing two models of the cookstove, viz. Model I and Model II. In order to achieve a clean combustion, the TEG cookstove Model I was provided with two separate chambers for the supply of primary and secondary air. A separate metal box was provided for the TEG assembly. Further, the TEG cookstove Model I was provided with an ash grate through which the primary air was entering into the hot charcoal bed. A schematic diagram of the TEG cookstove Model I is shown in Fig. 3.

A schematic diagram of the TEG cookstove Model II is shown in Fig. 4. From Fig. 4, it may be noted that a single chamber is used to

<table>
<thead>
<tr>
<th>Table 4: Equipment specifications.</th>
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<tbody>
<tr>
<td>Equipment</td>
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<tr>
<td>Digital thermometer</td>
</tr>
<tr>
<td>Multi-meter</td>
</tr>
<tr>
<td>Multi-meter</td>
</tr>
<tr>
<td>Anemometer</td>
</tr>
<tr>
<td>Tachometer</td>
</tr>
<tr>
<td>Digital balance</td>
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</table>

* Automatic calibration with reference weight.
supply the primary and secondary air required for clean combustion. The separate metal box provided in Model I, for accommodating the TEG components was eliminated in Model II and the space required by the TEG is made as an integral part of the cookstove in Model II without any projection. The separate chamber provided for the secondary air supply in Model I was also removed in Model II as a common chamber is used to supply the primary and secondary air. Further, the ash grate of Model I was removed and the primary air is supplied uniformly from the side walls at the bottom of the combustion chamber. With these arrangements in Model II, the design configurations for the TEG cookstove were finalized. The details of cost of the forced draft cookstove using an external power supply and those powered by TEG are presented in Table 6. From Table 6, it may be noted that the combination of the materials used in the TEG cookstove was optimized to bring down the cost, which is lower than the externally powered forced draft cookstoves. The cost of TEG powered cookstoves was brought down to 51% less than the cost of the cookstove referred in Ref. [18] and 54% with reference to Ref. [17]. Selection of the TEG and TEG related components has a strong influence on the overall cost of the cookstove as TEG accounts for 46% of the cookstove cost. Besides the benefit of reduced cost, one of the major advantages of a TEG powered cookstove is that it can work even without a backup power supply as it generates its own power.

### 4.2. Performance of the TEG

In the present study, the operating conditions of the TEG were finalized to keep the hot side of the TEG in the range of 300–310 °C when the cold side is in the range of 60–65 °C. With a temperature difference of 240 °C, the TEG produces a power output of 4.5 W, with 4.5 V and 1 A. The performance of the TEG was monitored by its output voltage continuously throughout the WBT. The performance of the TEG during the different phases of WBT by voltage output is shown in Fig 5. From Fig. 5, it may be noted that the TEG takes about 10 min to reach its maximum output. The power produced during the high-power phases of the WBT is higher than the power production rate during the simmering phase. The firepower of the cookstove has a strong influence on the power output of the TEG. The TEG could reach a maximum voltage of 4.5 V during the high-power phases and remain closer to an average of 3.5 V during the simmering phase.

A comparison of the performance of the TEG from the present study with the performance of the TEG from selected references is presented in Table 7. At a temperature difference of 160 °C, the maximum power output of a TEG module was 2.3 W [31]. The TEG takes about 50 min to reach its maximum power output of 4.2 W at a temperature difference of 256 °C [32]. A power output of 2.4 W

<table>
<thead>
<tr>
<th>Table 5: A comparison of the specifications of the TEG modules.</th>
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<tbody>
<tr>
<td>Component</td>
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<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Hot face — recommended</td>
</tr>
<tr>
<td>Cold face — recommended</td>
</tr>
<tr>
<td>Hot face — maximum</td>
</tr>
<tr>
<td>Flux</td>
</tr>
<tr>
<td>Cost of the TEG module</td>
</tr>
<tr>
<td>Cost by power output</td>
</tr>
</tbody>
</table>
was obtained at a temperature difference of 150 °C [33]. A maximum power output of 1.7 W was obtained at a temperature difference of 200 °C [34]. A power output of 8.3 W was obtained using four TEG modules, at a temperature difference of 155 °C which works out to be 2.1 W per module [35]. At 210 °C of temperature difference, 5.3 W power was produced when the design capacity of the TEG was at 5.9 W [36]. In the present study, the TEG was producing 4.5 W at a temperature difference of 240 °C. The performance of the DC blower selected for TEG operation was 2.1 W per module [35]. A t2 1 0 °C of temperature difference of 200 °C works out to be less than 1 W per module. TEG referred in Ref.[36] and the TEG of the present study is functioning at 90% of the design capacity. The TEG referred in Ref. [32] takes about 50 min to reach its maximum power output, whereas the TEG in the present study reaches its maximum power output within 10 min.

Four thermo electric generator modules were connected in series and the power output was 7.34 W at a temperature difference of 150 °C [37]. The maximum power output of 55 W was obtained by using 60 W TEG modules, when the hot face of the TEG was at 250 °C [38]. This works out to be less than 1 W per module. TEG power output was studied with variation in flue gas temperature which was used as a heat source [39]. Maximum power output of 0.35 W cm⁻² was obtained when the flue gas temperature was at 427 °C. In the present study, the power output of the TEG was 0.5 W cm⁻². Results of an analytical model were reported in Ref. [40]. A maximum power output of 3.98 W can be obtained at a temperature difference of 120 °C. The TEG module used in this study was producing 4.5 W at a temperature difference of 240 °C.

4.3. The performance of the DC blower selected for TEG operation

In TEG powered forced draft cookstoves, the function of the DC blower is an important factor which controls the efficiency of cookstoves as well as the efficiency of TEG. The cookstove is designed to have an average wood consumption rate of 1.0 kg h⁻¹.

For achieving a complete combustion of 1.0 kg of wood, 6.3 kg of air is required. The blower should be able to blow air at a rate of 7.5 kg h⁻¹ (20% excess air) to ensure complete combustion of wood. Supply of air at a rate less than the required airflow rate will lead to incomplete combustion and poor efficiency of the cookstove. When the airflow rate is less, the heat removal rate from the heat sink will accordingly be less resulting in an increase in the temperature of the TEG’s cold face. The high temperature of the cold face will result in a reduction in the power output of the TEG. Besides reduction in the power output, the temperature of the TEG’s hot face will increase beyond the preferred temperature which will damage the TEG. When the airflow rate is above the required flow rate, a major portion of the heat from the cookstove will be carried away by the excess air. Hence, supply of excess air will reduce the thermal efficiency of the cookstove. Considering these points, the blower was selected to maximize the power output of the TEG and the performance efficiency of the cookstove with clean combustion.

The performance of the blower was monitored throughout the water boiling test by measuring the speed (RPM) of the blower. The speed of the blower is a function of the power generated (power output) by the TEG. Further, power output is a function of voltage and current supplied to the blower. The power output of the TEG is directly proportional to the firepower of the cookstove. A table showing details of the performance of the blower along with the input voltage and current is presented in Table 8. The speed of the blower (in RPM) along with input voltage is shown in Fig. 6. From Fig. 6, it may be noted that the voltage supplied to the blower varies according to the firepower of the cookstove. During the initial startup phase, the speed of the blower increases gradually in proportion to the increase in the firepower of the cookstove. It takes about 10 min for the blower to reach its maximum speed.

It was observed that the speed of the blower was controlled by the power output from the TEG. The power output from TEG is at its maximum during the hot-start high-power phase, since the temperature difference between the hot face and cold face of the TEG is maximum during this period. The power output of the TEG is at its minimum during the simmering phase, since the temperature difference between the hot face and cold face of the TEG is at its minimum during this period. Hence, the quantity of air blown by the blower is high during the hot-start high-power phase and less quantity of air is blown when the cookstove is at its simmering phase. The positive aspect of the TEG powered forced draft cookstoves is that the airflow rate varies according to the firepower of the cookstove. The TEG operated blower supplies more air when more fuel is burnt and less air when less fuel is burnt. Hence, the air supply from the blower is automatically controlled by quantity of

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**Table 6**
Component wise cost breakup of the forced draft cookstoves.

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Component</th>
<th>Externally powered</th>
<th>Powered by TEG stove</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cost (US $)</td>
<td>Cost share (%)</td>
</tr>
<tr>
<td>1</td>
<td>The metal stove (made of SS sheet and multiple insulation layers)</td>
<td>30.0</td>
<td>50.0</td>
</tr>
<tr>
<td>2</td>
<td>A DC Fan to supply air for primary and secondary combustion</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>3</td>
<td>Power supply system</td>
<td>30</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>63</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

**Table 7**
A comparison of the TEG performance with selected references.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature difference</td>
<td>°C</td>
<td>[15] [32] [33] [35] [36]</td>
</tr>
<tr>
<td>Power output</td>
<td>W</td>
<td>4.5 2.3 4.2 2.4 2.1 5.3</td>
</tr>
</tbody>
</table>

---

**Fig. 5.** Performance of TEG during the different phases of WBT.
fuel supplied to the cookstove. Whereas, in case of a forced draft cookstove powered using an external power supply, it is complicated to control the burning rate of the fuel. The controllability of the firepower of turbo stoves is high at the higher ends and not as low as gas stoves at the lower ends [41]. Since, the power output from the TEG which controls the airflow to the stove is directly linked with the firepower of the cookstove it becomes comparatively easier to operate a TEG powered cookstove with a good control at a required firepower.

### 4.4. Performance of the TEG powered forced draft cookstove

The performance of the TEG powered forced draft clean combustion cookstove was evaluated by using the WBT version 4.2. The performance results of the TEG powered forced draft cookstove was presented in Table 9. From Table 9, it may be noted that the firepower during the cold-start high-power phase, it took about 23 min to boil 5.0 dm³ of water. However, during the hot-start high-power phase the stove took about 18 min only to boil 5.0 dm³ of water. During the simmering phase, the temperature of water was kept between 96 and 97 °C for 45 min.

#### 4.4.1. Firepower

The firepower of the TEG cookstove during the cold-start high-power phase was 3.43 kW and during the hot-start high-power phase was 3.97 kW. It may be noted that the firepower during the hot-start high-power phase is 16% higher than the firepower during the cold-start high-power phase. This increase in firepower is due to an increase in the burning rate of fuel wood as a result of an increase in the temperature in the combustion chamber.

During cold-start conditions, the temperature of the combustion chamber gradually increases along with an increase in the temperature of materials used for constructing the cookstove. A profile of the firepower of the TEG powered cookstove, during the different phases of WBT is shown in Fig. 7. From Fig. 7, it may be noted that during the cold-start high-power phase, it took about 23 min to boil 5.0 dm³ of water. However, during the hot-start high-power phase the stove took about 18 min only to boil 5.0 dm³ of water. During the simmering phase, the temperature of water was kept between 96 and 97 °C for 45 min.

#### 4.4.2. Turndown ratio

The turndown ratio is an important factor, which determines fuel saving during actual cooking conditions. The duration of the simmering phase is almost three times more than the duration of the hot-start high-power phase. Higher fuel consumption during the simmering phase indicates higher heat loss and low thermal efficiency. A cookstove having a high thermal efficiency during the hot-start high-power phase and a low TDR will consume more fuel during actual cooking conditions. A comparison of firepower and TDR along with the overall efficiency of the TEG powered cookstove is presented in Table 10. From Table 10, it may be noted that the overall efficiency of the cookstove is 44% and the TDR of the TEG powered cookstove is 3.6.

During the simmering phase, the TEG powered cookstove was consuming only 27.7% of fuel as compared to the fuel consumed during the hot-start high-power phase. Further, a profile of the firepower and TDR observed during the WBT is shown in Fig. 9.

### Table 8

Performance results of the DC blower.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Current (mA)</th>
<th>Power (W)</th>
<th>Fan speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>4.7</td>
<td>0.002</td>
<td>265</td>
</tr>
<tr>
<td>0.64</td>
<td>11.2</td>
<td>0.007</td>
<td>395</td>
</tr>
<tr>
<td>0.99</td>
<td>26.5</td>
<td>0.026</td>
<td>766</td>
</tr>
<tr>
<td>1.02</td>
<td>27.8</td>
<td>0.028</td>
<td>781</td>
</tr>
<tr>
<td>1.38</td>
<td>43.5</td>
<td>0.060</td>
<td>975</td>
</tr>
<tr>
<td>1.82</td>
<td>62.7</td>
<td>0.114</td>
<td>1170</td>
</tr>
<tr>
<td>2.08</td>
<td>74.0</td>
<td>0.154</td>
<td>1238</td>
</tr>
<tr>
<td>2.14</td>
<td>76.7</td>
<td>0.164</td>
<td>1262</td>
</tr>
<tr>
<td>2.36</td>
<td>86.2</td>
<td>0.204</td>
<td>1348</td>
</tr>
<tr>
<td>2.53</td>
<td>93.7</td>
<td>0.237</td>
<td>1388</td>
</tr>
<tr>
<td>2.83</td>
<td>106.7</td>
<td>0.302</td>
<td>1483</td>
</tr>
<tr>
<td>3.05</td>
<td>116.5</td>
<td>0.355</td>
<td>1642</td>
</tr>
<tr>
<td>3.85</td>
<td>151.1</td>
<td>0.582</td>
<td>1923</td>
</tr>
<tr>
<td>4.56</td>
<td>182.7</td>
<td>0.833</td>
<td>2114</td>
</tr>
<tr>
<td>5.00</td>
<td>201.2</td>
<td>1.006</td>
<td>2235</td>
</tr>
</tbody>
</table>

#### Table 9

Performance results of the TEG powered forced draft cookstove.

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Cold-start high-power phase</th>
<th>Hot-start high-power phase</th>
<th>Simmering phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duration (min)</td>
<td>Fuel wood consumption (kg)</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>1</td>
<td>22.0</td>
<td>0.270</td>
<td>42.7</td>
</tr>
<tr>
<td>2</td>
<td>24.0</td>
<td>0.280</td>
<td>41.9</td>
</tr>
<tr>
<td>3</td>
<td>24.0</td>
<td>0.270</td>
<td>42.9</td>
</tr>
<tr>
<td>4*</td>
<td>23.3</td>
<td>0.273</td>
<td>42.3</td>
</tr>
</tbody>
</table>

* Average value of the results was obtained from three experiments.
4.4.3. Energy consumption rate

The energy consumption rate of the TEG powered cookstove was estimated by monitoring the fuel consumption during the different phases of WBT. It is observed that the wood consumption rate during the hot-start high-power phase is relatively more when compared with the wood consumption rate during the simmering phase. Although the fuel consumption rate during the simmering phase is less when compared to the fuel consumption rate during the hot-start high-power phase and also the duration of the simmering phase is much longer than the hot-start high-power phase. Hence, the total energy consumed during the simmering phase is higher than the hot-start high-power phase.

The energy consumption rate at different phases of the WBT was estimated. A comparison of the energy consumption during the different phases of the WBT is shown in Fig. 10. It may be noted from Fig. 10, that the energy consumed during the hot-start high-power phase is marginally less when compared with the energy consumed during the cold-start high-power phase. Energy consumption during the simmering phase is higher than the high-power phases of the WBT.

4.5. Effect of cookstove’s cost on large scale adoption

Actually, by definition, it is impossible to persuade to buy something beyond their capacity to afford it. For a successful entrepreneurship development and commercialization, pricing and financial scheme for cookstoves are considered as key requirements [30]. Price of the cookstoves can be a significant barrier for their adoption and a payback period of 1–3 months is preferred by the consumers [19]. The cost of cookstove is an important factor for large-scale dissemination. A turbo stove costing above US $ 80 (in 2010) is beyond the paying capacity of the poor [13]. There are many semi-gasifier stoves priced above US $ 50 (in 2010). These stoves are powered by a battery backup or an external power supply. In the present study, attempts were made to design and develop a TEG powered forced draft cookstove which its users can afford to buy. Financial sustainability of improved cookstove sales to households remains un-assured [43]. The results of the performance evaluation of three improved cookstoves along with a comparison to the traditional cookstove by two organizations were reported in Ref. [44]. While the traditional cookstove performs at 15–16% efficiency, the improved cookstoves perform at 17–19% efficiency [44]. It was observed that the improvement in the efficiency of cookstoves is only in the range of 1–3%, which may not contribute any significant reduction in fuel consumption [44]. Forced draft cookstoves work relatively at a higher efficiency. The TEG powered forced draft cookstoves operates with an efficiency of 44%, i.e. about 25% more than the improved cookstoves and 27% more than the traditional cookstoves. With an efficiency of 44%, the TEG powered forced draft cookstove can result in 62% of fuel saving as compared to traditional cookstoves. The traditional cookstoves used in Vietnam were working at an efficiency of 17.4% whereas improved cookstove from India operates with an efficiency of 26.6% [45]. Considering the above, an improved cookstove that works on natural draft mode can save up to 34.6% of wood as compared to traditional cookstoves and a forced draft cookstove powered by TEG can save up to 62% of wood.

The annual global burden due to indoor air pollution created by biomass cookstoves is estimated to be about US $ 232,388 million

![Fig. 7. Water temperature during the different phases of WBT.](image)

![Fig. 8. Firepower during different phases of WBT.](image)

![Fig. 9. Profile of the firepower and turndown ratio.](image)

Table 10: Firepower, turndown ratio and efficiency of the TEG powered cookstove.

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Cold-start high-power (kW)</th>
<th>Hot-start high-power (kW)</th>
<th>Simmering (kW)</th>
<th>Turndown ratio (energy fraction)</th>
<th>Overall efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.58</td>
<td>4.12</td>
<td>1.13</td>
<td>3.65</td>
<td>44.0</td>
</tr>
<tr>
<td>2</td>
<td>3.41</td>
<td>3.81</td>
<td>1.08</td>
<td>3.53</td>
<td>44.0</td>
</tr>
<tr>
<td>3</td>
<td>3.29</td>
<td>3.98</td>
<td>1.10</td>
<td>3.61</td>
<td>44.1</td>
</tr>
<tr>
<td>4*</td>
<td>3.43</td>
<td>3.97</td>
<td>1.10</td>
<td>3.60</td>
<td>44.0</td>
</tr>
</tbody>
</table>

* Average value of the results was obtained from three experiments.
A TEG powered battery charger was studied using a DC converter [52]. In the present study, the blower was operating at 4.5 V with a power consumption of 0.8 W. Since, the blower used in the TEG stove consumes only 0.8 W out of the 4.5 W of power generated by the TEG, the remaining 3.7 W of power can be used to charge a battery. The power stored in the battery can be used for various options as and when required.

The output voltage from TEG varies in the range of 3.5–4.5 V. The power output of a TEG is susceptible to the variation in the temperature of the heat source [51]. The electricity produced from TEG was used to charge a 3.3 V lithium-ion phosphate battery [37]. A single TEG module was used directly to charge a 3.3 V LiFePO4 battery without using DC–DC converter [52]. In the present study, the power produced from TEG was used to charge a 3.7 V battery. For charging a battery of 3.7 V, the power output of the TEG should always be greater than 3.7 V. However, in practical scenarios the power output of the TEG varies according to the firepower of the cookstove and at sometimes is less than 3.7 V. Hence, there is a need for an intermediate electronic circuit to maintain the output voltage constantly above 3.7 V.

Multi-utility options like mobile phone charging and LED lighting can be provided by designing and connecting a battery charger to the TEG powered cookstove using USB ports. Since, the battery has a capacity of 3.7 V output, the power output of the USB ports has to be raised to 5 V in order to charge the battery. Accordingly, the USB ports should be capable of providing a continuous power supply of 5 V. In order to boost the output voltage from the USB ports a DC–DC converter was used. The DC–DC converter increases the power output to the battery by 15% in comparison with the direct charging [11].

A TEG powered battery charger was studied using a DC–DC converter. A diagram depicting the concept and key components of a TEG powered battery charger with a 5.0 V DC output for multi-utility options is shown in Fig. 11. From Fig. 11, it can be seen that

![Energy consumption during different phases of the WBT.](image)

Since, 46% of the total cost of the TEG powered cookstove pertains to the TEG module used in the cookstove, it is essential to justify the value of the TEG powered cookstoves to its users by providing value added features. One such feature would be to provide multi-utility options like mobile phone charging and LED lighting. TEG powered cookstove can be used to produce a small amount of power for people who do not have access to electricity, to charge their mobile phones and operate LED lights. With advancements in technology and the need for effective communication, mobile phones are now being widely used by remote rural population, even though they do not have any access to grid power. The daily average energy requirement to charge a mobile phone is 7 Wh and 5 million mobile phone users are without access to electricity [48]. People spend about US $ 4–5 per month to get their mobile phones charged from private vendors. People in remote villages can use TEG powered cookstoves to charge their mobile phones instead of relying on private power providers. Considering the benefit of mobile phone charging, the payback period for TEG powered cookstoves is 12 months. Mobile phone charging is a viable economic activity where the grid is absent [49].

In India the rural households, at locations where no electricity is available, spend about 0.5 US $ per day on fuel for lighting [50]. In other words, the expenditure incurred on fuel for lighting purposes is US $ 15 per month. Since, the payback period for TEG powered cookstoves in such cases is 4 months, people may use TEG powered cookstove to operate LED lights and need not buy fuel for lighting purposes.

Considering the above features, TEG powered cookstoves can increase the adoptability of forced draft cookstoves, by providing multi-utility options and thereby increasing monetary benefits to its users.

### 4.6.1. Battery charger

It may not be feasible that the multi-utility option such as mobile phone charging and LED lighting are available only when the cookstove is in use. It is not a prerequisite that the charging of mobile phones/LED lights and cooking will happen at the same time. To overcome this issue, it is preferable to charge a battery when the cookstove is in operation and thereafter uses the power stored in the battery as and when required.

The TEG powered cookstove produces electric power at a rate of 4.5 W. The power supplied from TEG to the fan is 1.0 W [15]. In the present study, the blower was operating at 4.5 V with a power consumption of 0.8 W. Since, the blower used in the TEG stove consumes only 0.8 W out of the 4.5 W of power generated by the TEG, the remaining 3.7 W of power can be used to charge a battery. The power stored in the battery can be used for various options as and when required.

The output voltage from TEG varies in the range of 3.5–4.5 V. The power output of a TEG is susceptible to the variation in the temperature of the heat source [51]. The electricity produced from TEG was used to charge a 3.3 V lithium-ion phosphate battery [37]. A single TEG module was used directly to charge a 3.3 V LiFePO4 battery without using DC–DC converter [52]. In the present study, the power produced from TEG was used to charge a 3.7 V battery. For charging a battery of 3.7 V, the power output of the TEG should always be greater than 3.7 V. However, in practical scenarios the power output of the TEG varies according to the firepower of the cookstove and at sometimes is less than 3.7 V. Hence, there is a need for an intermediate electronic circuit to maintain the output voltage constantly above 3.7 V.

Multi-utility options like mobile phone charging and LED lighting can be provided by designing and connecting a battery charger to the TEG powered cookstove using USB ports. Since, the battery has a capacity of 3.7 V output, the power output of the USB ports has to be raised to 5 V in order to charge the battery. Accordingly, the USB ports should be capable of providing a continuous power supply of 5 V. In order to boost the output voltage from the USB ports a DC–DC converter was used. The DC–DC converter increases the power output to the battery by 15% in comparison with the direct charging [11].

A TEG powered battery charger was studied using a DC–DC converter. A diagram depicting the concept and key components of a TEG powered battery charger with a 5.0 V DC output for multi-utility options is shown in Fig. 11. From Fig. 11, it can be seen that
the blower is directly connected to the output terminals of the TEG. A Zener diode is connected in parallel connection to the TEG’s output terminal to maintain the circuit at 4.3 V; a Schottky diode is used to avoid the reverse flow of the current when charging the battery and a DC–DC converter is used to increase the power output from 3.7 V supplied by the battery to 5 V for charging mobile phones and for LED lighting. A view of the TEG operated cookstove working with multi-utility options is shown in Fig. 12. From Fig. 12, it may be noted that the power generated from the TEG powered cookstove can be used for battery charging, mobile phone charging and LED lighting.

5. Conclusions

Attempts were made to design and develop a TEG powered forced draft cookstove with the objectives of clean combustion with higher efficiency. The TEG powered forced draft cookstove was designed with multi-utility options like mobile phone charging and LED lighting. The efficiency of the TEG powered forced draft cookstove was 42.3% during the cold-start high-power phase, 46.9% during the hot-start high-power phase and 43.1% during the simmering phase. The overall efficiency of the TEG powered forced draft cookstove was 44%, during the period of the WBT. This is about 16% more than the efficiency of the improved cookstoves, which operate on natural draft mode. The firepower of the TEG powered forced draft cookstove was 3.43 kW during the cold-start high-power phase, 3.97 kW during the hot-start high-power phase and 1.1 kW during the simmering phase. TDR is an important parameter which indicates the fuel saving potential in actual cooking conditions. The TEG powered forced draft cookstove was working with a TDR of 3.6, i.e. the firepower during the simmering phase was 63% less than the firepower during the hot-start high-power phase.
A TEG module having a capacity to produce 5.0 W at 5.0 V DC was used in the TEG powered forced draft cookstove. The TEG was operating with a maximum power output of 4.5 W at a temperature difference of 240 °C between the hot side and cold side. The TEG used in the cookstove was working at 90% of the design capacity of the power output. The performance of the TEG used in the present study was compared with the performance of TEGs from selected references. The TEG was tested for multi-utility options like mobile phone charging and LED lighting. Out of the 4.5 W power produced from the TEG, 0.83 W was consumed by the blower used in the TEG stove and the remaining 3.67 W was available for applications like mobile phone charging and LED lighting. The TEG powered forced draft clean combustion cookstove developed during the present study can be used to reduce indoor air pollution as the forced draft cookstoves provide a clean combustion. Due to increase in the efficiency of the TEG powered forced draft cookstove, about 61% of fuel (wood) can be saved in comparison with the wood consumption of traditional cookstoves. The cost of the TEG system and the cookstove was optimized by selection of appropriate material and components. The cost of the cookstove developed in the present study is marginally lower than the externally powered forced draft cookstoves and is much less than the TEG powered forced draft cookstoves. The TEG powered forced draft cookstove can provide cooking and lighting solution for the large population who does not have access to electricity and rely on biomass alone for cooking.

Acknowledgement

We are grateful to Dr. R.K. Pachauri, Director General, TERI for his continuous encouragement and support. We would also like to thank Mr. Amit Kumar, Director, Energy Environment Technology Development Division of TERI for providing valuable support to conduct the study.

Nomenclature

Qf quantity of heat flow across the TEG components at any given time, W
ks thermal conductivity of the material used to transfer the heat from combustion chamber to TEG, W m⁻² K⁻¹
Δt1 temperature difference between the hot surface of the TEG and the heat source, °C
Δt2 temperature difference between the hot surface of the TEG and the heat sink, °C
ks thermal conductivity of TEG module, W m⁻² K⁻¹
d2 thickness of the heat sink used to remove the heat from the TEG, m
Δt3 temperature difference between the surface of the heat sink and ambient air, °C
ρ3 contact area between the surface of the heat sink and ambient air, m²
FWp quantity of fuel wood consumed during a particular phase of xi during WBT (i varies from 1 to 3 which represent the three phases WBT), kg
Np number of fuel packets (of 125 g) consumed during a particular phase of xi during WBT, kg
RPi quantity of fuel wood remaining in the last packet used during a particular phase of xi during WBT, kg
ηsp efficiency of the cookstove during the high-power phases of WBT (j represents the cold-start high-power phase and hot-start high-power phase), %
Ww weight of water used to boil during WBT, kg
Wv weight of the vessel used to boil the water, kg
Cr specific heat of material of the vessel, used to boil the water, kJ kg⁻¹ K⁻¹
Ti initial temperature of the water, °C
Tf final temperature of the water, °C
Le latent heat of evaporation of water, kJ kg⁻¹
CVfw caloric value of the fuel wood used during WBT, MJ kg⁻¹
ηsp efficiency of the cookstove during simmering phase, %
Fp repower during a particular phase of xi during WBT, kW
dp temperature need to be raised to boil the water from the standard initial temperature specified in WBT protocol, °C
Qw quantity of water used during WBT, dm³

Abbreviations

A Ampere
ER equivalence ratio
GM geometric mean
LED light emitting diode
SD standard deviation
SFC specific fuel consumption
SS stainless steel
TDR turndown ratio
TEG thermo electric generator
UNF United Nations Foundation
UNIDO United Nations Industrial Development Organization
V volt
W watt
WBT water boiling test
WHO World Health Organization

References


